GROUNDING OF AC AND DC LOW VOLTAGE AND MEDIUM VOLTAGE DRIVE SYSTEMS

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Abstract: The grounding of ac and dc drive systems should detect and clear ground faults both on the source and load side of the converters. Most drive systems are separately derived through a step-down transformer, which serves as a drive isolation as well as rectifier transformer. Isolation transformers on individual or group drive systems, downstream of main substation transformers are also common. An output isolation transformer on an ac drive will isolate the drive electronics, step-up the ac voltage from the inverter section and also serve to control high line-to-ground voltages on the motor windings. The grounding system has profound effect upon the continuity of operations, loading of the solid state devices and common mode voltages. The paper discusses the various possibilities of grounding of low voltage and medium voltage drive systems and shows that a high resistance grounding system can be often implemented to permit continuity of operations, allow fault detection and limit the transient overvoltages.

1. INTRODUCTION

The grounding of industrial and commercial plant distributions is discussed in the literature [1,2,3,4,5,6,7,8], yet the specific requirements of grounding of drive systems are not adequately covered. In many respects, these grounding requirements are identical to power system grounding practices, yet special considerations apply. The paper discusses the various methods of grounding based upon the following considerations:

(1): Continuity of the processes and preventing immediate shutdowns.

(2): Limiting the transient overvoltages to ground.

(3): Meet NEC requirements and personal safety.

(4): Detect, alarm and/or selectively isolate the faulty section.

(5): Limit insulation stresses on electrical equipment.

(6): Consider common mode voltages that will appear on motor insulation and cables in ac drive systems.

Single-line-to-ground faults are the most common types of faults in the industrial distribution systems and the fault damage is proportional to the square of the fault current. Thus, the fault current should be reduced by impedance grounding. The choice lies between no ground fault current on the first line-to-ground fault (ungrounded systems) to fault currents limited to 200 A to 400 A by low resistance grounding.

The present trends in grounding the large drive systems favor high impedance grounding and fault detection. An analysis of wye connected resistor attenuators, with a common sensing resistor connected between the wye-point to ground has been developed in Section VI of the paper. This shows that a high resistance fault of the order of 10 MΩ can be detected in a drive system of 4160 V at rated voltage output of the drive. While ensuring continuity of processes, the electrical and drive systems are subjected to minimum of current and voltage shocks.

II. GROUNDING METHODS

Solidly Grounded

There is no intentional impedance between the system neutral and ground. These system meet the requirements of a “effectively grounded” system, in which ratio X/L, is positive and less than 3.0 and the ratio R / X is less than 1, where X, X, and R, are the positive sequence reactance, zero sequence reactance and zero sequence resistance respectively. Though these system will provide effective control of overvoltages which become impressed on or self-generated in the power system by insulation breakdowns and restriking faults, these are not generally used with drive systems.

The consequences of a ground fault in a drive system depend upon its topology, and exactly where the fault takes place. In general, the fault may occur at:

(a) The input wiring or components up to the ac terminals of the input rectifiers or thyristors: For all topologies, this results in ac fault current limited only by the source reactance. In a solidly grounded system this fault current will approach or exceed three-phase fault current and should be cleared by fuses or instantaneous overcurrent devices on breakers.

(b) On the dc bus downstream of the input rectifiers: For diode rectifiers, this will result in an ac fault current limited by source reactance and will be cleared by fuses or breakers as in (a). In case of thyristor converters, the fault current, for
large phase-back angles, may be low enough to be cleared by gate interruption.

(3) On dc bus downstream of link reactor in current-fed topologies: In this case the line fault current rises so slowly so as to permit timely gate interruption.

(4) At the drive output terminals or at the motor terminal box or motor windings: If the topology is current fed, the situation is same as in (c). In voltage-fed circuits with a dc link capacitor, the situation is more complex. If the link capacitor is fully charged, there is no path through the inverse parallel diodes, thus, any ground fault must flow through the output transistors or IGBT’s (Insulated Gate Bipolar Transistors). As these are protected by desaturation detectors and/or IOC’s, ground currents are quickly extinguished by withdrawal of gate drive. However, if the dc capacitor is not charged, and power is applied to a drive with a ground fault in the output, a large transient ground fault current will flow through the link capacitor and the inverse parallel diodes.

Where a unit substation transformer serves a mixed load including drives, and is solidly grounded, an isolation transformer can be interposed to isolate the drive section. The separately derived system can then be provided with a different grounding method.

The alternating current circuits and systems described in NEC, Article 250-5 must, however be solidly grounded [3]. The ungrounded control circuits at 120/240 V are not acceptable and will be a violation of NEC.

The immediate shutdown of the processes and high fault currents make this method of grounding of little use for the drive systems. An exception being the corner grounded delta secondary systems, still in use for small three-phase loads in the rural distribution systems, mainly because of economy.

Low resistance ground:

The ground fault current is limited to approximately full load current or lower. In the industrial distribution systems the neutrals of medium voltage transformers are commonly grounded through 400 A or 200 A resistors. Like the solidly grounded systems, the low-resistance grounded systems provide effective control to safe levels of the overvoltages generated in the power system by resonant capacitive-inductive circuits and restricting ground faults. Yet, the ground fault currents cannot be allowed to be sustained and tripping by phase and/or ground overcurrent devices must be provided for. Thus, an immediate shut down of the processes occurs. The low-voltage drive systems are rarely grounded through a low resistance.

Fig. 1 shows a low resistance grounding system for a 5/7 MVA substation transformer, which serves a number of 500-hp ac drive motors. The wye connected secondary winding of the isolation transformer on the output side of each 500hp ac drive is also low resistance grounded. As a number of such drives are connected to the same unit substation transformer, low resistance grounding permits selective ground fault clearance. The 5/7 MVA transformer neutral connected ground fault relay should trip an upstream breaker to clear a ground fault in the transformer secondary windings. The secondary of the drive isolation transformer is high resistance grounded and fault detection between the input and output isolation transformers is provided by device 59.

In low resistance grounded system, with fault current limited to 400 A and the pickup sensitivity of the modern solid state ground fault devices of 5 A or even lower, approximately 98.75% of the transformer and motor windings can be protected. The incidence of a ground fault towards the neutral decreases as the square of the winding turns and thus a sensitive ground fault protection is obtained. The drawback is the immediate interruption of the processes.
High resistance grounding:

This is a grounding method of choice for the drive systems and its various configurations are shown in Fig. 2. Fig. 2(a) is applicable to low voltage systems, Fig. 2(b), 2(c), and 2(d) can be applied to medium voltage systems. Figs. 2(c) and 2(d) are applicable when system neutral is not available.

The effective control of steady state and transient overvoltages requires that the fault current $I_f$ through the grounding resistor is at least equal to or greater than $I_{r1}$, where $I_{r1}$ is the resistive component of the ground fault current through the grounding resistor on a single-phase-to-ground fault and $I_{c}$ is the capacitive current returning to ground due to distributed phase capacitance. Thus, the total ground fault current is at least $\sqrt{2} I_{c}$.

Configurations in Figs. 2(b), 2(c), and 2(d) will operate for a fault on the ac side, but are not suitable for detection of a fault on the converter side.

Ungrounded systems:

In an ungrounded system, there is no intentional connection to ground except through potential transformers or metering devices of high impedance. Therefore, in reality, an ungrounded system is coupled to ground through the distributed phase capacitances. It is difficult to assign $X_R/X_0$ and $Z_R/X_0$ values for ungrounded systems. The ratio $X_R/X_0$ is negative and may vary from low to high values and COG (Coefficient of grounding) may approach 120%[7].

The ungrounded systems provide no effective control of transient and steady state voltages above ground. A possibility of resonance with high voltage generation, approaching five times or more, of the system voltage exists for values of $X_R/X_0$ between 0 and -40 [7,9]. For the first line-to-ground fault, no fault current flows and the continuity of operations can be sustained, though the unfaulted phases will rise to line-to-line voltage, i.e., the voltage to ground will be $\sqrt{3}$ times the normal. On a second ground fault the single-phase fault turns into a two-phase to ground fault and enough ground fault current may flow to actuate the overcurrent relays.

All unremoved ground faults put greater than normal voltage on system insulation. The possible requirement of increased conductor insulation in ungrounded systems is discussed further in the paper.

If 50% of the drive isolation transformers are connected delta-wye, and remaining 50% delta-delta there will be a 30-degree phase shift in the secondary voltages of the two sets of isolation transformers with respect to the primary voltage, and lower order harmonics of 5th and 7th will be canceled, though a complete cancellation may not take place, as the loads will not be exactly identical [10]. Often these isolation transformers have been left ungrounded and sometimes, even a ground fault detection system is missing. This should not be acceptable, and as a minimum a ground fault detection and alarm system should be provided with ungrounded systems. A high resistance grounded system will achieve the same objectives of continuity of operation, alarming the first ground fault and also controlling the voltages due to inductive-capacitance resonances.

III. CHARACTERISTICS OF HIGH RESISTANCE GROUNDING SYSTEM

Fig. 3 shows the current and voltages in a high resistance grounded system under no fault conditions and for a fault on the ac side. The characteristics of this system are:

(a): For no fault condition the system neutral is held at ground potential. Assuming same phase to ground distributed capacitances, the current returning through the neutral resistor is:

$$I_a + I_b + I_c = 0 \quad (1)$$

This is shown in Fig. 3(b). Mathematically:

$$I_a = V<00/X_{ov}, I_b = V<120^o/X_{ov}, I_c = V<120^o/X_{ov} \quad (2)$$

In a balanced symmetrical three-phase system, the phase capacitance to ground can be assumed equal. Each phase capacitance to ground is a summation of the capacitances to ground of cables, buses, transformers, and surge arresters. The capacitive charging current in the low voltage distribution system of drives, served from transformers up to 2000 kVA rating will rarely exceed 1-2 A, provided there are no secondary surge arresters in the distribution system.
(c): The current through the grounding resistor $I_g$ should be equal to or greater than the distributed capacitive current. Referring to Fig. 3(c), phase A capacitance is shorted to ground due to fault and does not contribute to the flow of ground current. The capacitive component of the ground fault current, $I_{ct}$, is given by:

$$I_{ct} = I_{ct} + I_{ct} = 3I_{a} = 3I_{b} = 3I_{c}$$

(3)

The phase capacitance currents $I_{ct}$ and $I_{ct}$ are $\sqrt{3}$ times the capacitance currents $I_{a}$ and $I_{b}$ respectively, because the line-to-ground voltages on unfaulted phases are $\sqrt{3}$ times higher. Thus, for ac systems the resistor can be sized based upon the following equation:

$$R_n = \frac{V_{ln}}{I_{ct}}$$

(4)

Where $V_{ln}$ is the line to neutral voltage in rms.

The ground fault current magnitude is vectorial sum of $I_{ct}$ and $I_{c}$ i.e. the resistor does not carry all the ground fault current, as shown in Fig. 3(e).

The above is true for faults in the ac system, what about faults on the dc side, on the output of the converter?

(d): Fig. 4 shows ground fault on the dc side of a six-pulse rectifier circuit. The ground fault current is mainly limited by the grounding resistor, as the sequence impedances of the other components in the fault current path are comparatively smaller than the grounding resistor. This fault current is a dc current. The rectifier devices on one side of the bridge carry a current which is the sum of the load current plus the ground fault current. If this current is limited to a small percentage of the full load current, say not exceeding 5 A, continuous operation can be sustained and immediate shut down is not required.

The magnetic materials used in the power transformers are applied just below the knee point of the magnetization curve. Direct currents more than a few percent of the transformer full load current in the secondary windings can produce enough saturation to give rise to large primary currents and operation of transformer fuses. For high resistance grounded systems, the currents will be limited to 2-5 A, and these should not be of concern to cause high primary saturation currents.

High resistance grounding of Low voltage systems:

In low voltage systems, the wye connected transformer neutrals are directly connected to a grounding resistor. To properly select a resistor the following considerations are applicable:
Where $E_{dc}$ is the open circuit dc voltage on the output of the converter.

Thus, for an input ac voltage of 480 V, the dc output voltage is approximately 648.5V. 2A continuously rated resistor will have an ohmic value of 162 ohm and its wattage rating will be 17% higher than that of resistor used on the ac system alone.

A continuously rated stainless steel edge wound resistor, tolerances not exceeding 10% of the design value and temperature rise limited to 385° C [12] will be an appropriate choice.

**Medium voltage systems**

The high resistance grounding system consists of a distribution transformer, loaded with secondary resistor, as shown in Fig. 2(b). The distributive capacitive current increases as square of the voltage and should be calculated as for low voltage systems. The required primary resistance can be calculated using (4). The secondary resistance is given by:

$$R_{sec} = \frac{R_n}{N^2}$$

(6)

Where $R_{sec}$ is the secondary resistance and $N$ is the turns ratio of the single-phase step down transformer. The primary windings of the transformer must be insulated for line-to-line voltage and the transformer should be rated on a continuous basis if immediate fault isolation is not planned.

This system with a step down transformer cannot be applied when detection of ac as well as dc faults is required. A dc current through the transformer windings will only saturate the core. A configuration of resistors as shown in Fig. 5 can be applied. This permits connection of a voltage relay across the resistor from the common resistor wye-point to ground, for alarming a ground fault.

Fig. 5 also shows ground fault detection and alarm scheme for a fault on the dc bus. The differential voltage on occurrence of a ground fault between dc(+ ) and dc(- ) buses is detected. A fault close to the center of the motor windings may not be detected, depending upon the sensitivity of the scheme.

**IV. GROUND FAULT DETECTION AND PROTECTION IN HIGH RESISTANCE GROUNDED SYSTEMS**

**Pulsing type ground fault detection equipment:**

A pulsing type of ground fault equipment consists of a ground voltage relay, a cycle-timer, a tapped grounding resistor and a pulsing contactor [6]. A part of the grounding resistor is shorted and reinserted at a frequency of approximately 20 cycles per minute. The current pulses are generally twice the continuous current level. A clip-on ammeter is used to detect the faulty section by tracing the path of the current pulses.
This system is not suitable for detecting a fault on the dc side. Fig. 4 shows that ac pulses will be rectified and only a variation in the dc current will occur, which can't be picked up by the portable clip-on-detector.

Current transformer operated overcurrent devices:

These devices will not operate for a fault on the dc side. A dc current through a current transformer will only saturate its core and no output will result.

Characteristics of device 59

A single-phase-to-ground fault will result in an increased current flow through the grounding resistor, and the increased voltage developed across a voltage relay can signal a ground fault. Referring to Fig. 3, assume that the ground fault is limited to 2A maximum, a ground resistance of 162 ohms tapped in the middle is provided and primary ac voltage is 480 V rms, line-to-line. A high frequency current flows through the ground resistor due to neutral displacement and the modulation frequency of the drive. Some out of balance capacitance current is also present as the three-phase ac system is not perfectly symmetrical. Let the magnitude of this current be 0.5A rms.

The capacitance current due to distributive capacitances can be accurately calculated. Let the magnitude of this current be also 0.5A rms.

Following voltages are developed across overvoltage device connected between mid-point of the 162 Ω resistor and ground:

Voltage developed across the voltage relay under normal operation (This is a harmonic voltage) = 40.5 V rms
Current for an ac side fault = 1 A
Voltage developed for an ac fault = 81 V rms
Current for a dc side fault = 2 A
Voltage developed across the resistor for a dc fault = 162 V dc

Thus, the 59 device should be set to pickup above, say, 50 volts to avoid nuisance trips. It should respond to ac 60 Hz harmonic as well as dc voltages developed across the neutral resistor. A voltage relay incorporating full wave input rectifier and dc sensing coil will be suitable. The relay should be high impedance type, typically of 3000 ohms coil or more, so as not to effect the settings.

IV. INSULATION STRESSES

In high resistance grounded systems or ungrounded systems, the single-line-to-ground fault on the ac side gives rise to voltage stresses equal to 3 times the normal.

Low voltage Cables:

ICEA publication No. S-61-401, NEMA WCS (r1979) [13] specifies following guide lines for selection of cable insulation:

100 percent level = Ground fault cleared as rapidly as possible, but in any case less than one minute.

133 percent Level = This level corresponds to that formerly designated for ungrounded systems. Ground fault cleared in one hour.

173 percent Level = Time required to de-energize the system is indefinite.

Thus, a 173% level of conductor insulation is required when operation with a single-phase-to-ground fault exceeds one hour. However, no tables for 173% insulation level are provided, and this standard recommends consultation with the cable manufacturer. The insulation levels specified in NEC for 600 V grade cables correspond to 100% and 133% level of Table 3-1 of this standard, depending upon the type of insulation. Some cable manufacturers are of the opinion that intrinsic strength of thin sections of insulation used for cable insulations is approximately 500 volts per mil.
Consequently, the thickness of insulation specified in NEC are more than adequate to withstand any of the voltages encountered even in 600 V ungrounded systems. Other manufacturers recommend 2000 V grade cables. Considerations should also be given to the highest system operating voltages. Ref.[13] specifies that the actual voltage on the cables shall not exceed the rated circuit voltage by more than 5% during continuous operation or 10% during emergencies lasting not more than 15 minutes. This is of importance for 600 V nominal phase-to-phase systems. Dc no load voltage of six pulse rectifier systems will be 648V and 810 V respectively for 480 V and 600 V ac three-phase systems.

Medium voltage cables

For the medium voltage cables, 2000 to 8000 volts the thickness of insulation for 100% and 133% insulation levels for shielded and non shielded construction are specified in Tables 310-63 and 310-64 of NEC. Again with 133% insulation, the faulty section should be deenergized in one hour. 5 kV grade, 133% insulation level cables will be suitable for 2.3 kV drive systems. For 4 kV drive systems, a cable insulation of 8 kV will be an appropriate choice.

Low voltage motors

No specific tests have been provided in NEMA and ANSI for motors to be used on high resistance grounded or ungrounded systems. The dielectric test voltage is equal to twice the rated voltage plus 1000V for one minute. The higher voltage to ground on unfauluted phases will have minimal effects on the life of the insulation.

Medium voltage motors

The insulation of the medium voltage motors may not withstand higher line-to-ground voltages on the unfaulted phases and the motor manufacturer should be consulted.

Irrespective of the grounding method, the ac motors for the drive systems should meet the requirements of MG 1-1993, part 30 and 31[14,15].

Surge arresters

The surge arresters should be selected for ungrounded systems, considering the possible voltage excursions that may occur in the distribution system. For gapless surge arresters, the maximum continuous operating voltage (MCOV) of the arrester should be at least equal to the system line-to-line voltage.

Other electrical equipment

The effect of higher voltages to ground on other electrical equipment such as motor controllers, switchgear and transformers cannot be easily analyzed, as there are no guide lines or available standards. The equipment manufacturer should be consulted.

V. COMMON MODE VOLTAGES IN AC DRIVE SYSTEMS

Origin of common mode voltages

In a balanced three-phase power supply system, the phase vectors of voltages sum to zero, the neutral point is stationary under no fault conditions and is held at ground. In a three-phase, six pulse bridge rectifier circuit, only two phases conduct at a time. Fig. 6 shows the dc plus and negative voltages to the center point M. These voltages do not add to zero and the point M oscillates around the neutral at three times the supply frequency. The dc positive and negative buses have a common mode voltage and its magnitude changes with the bridge firing angle. The peak of this voltage is approximately 0.5 times $V_{in}$, where $V_{in}$ is the peak line to neutral input voltage.

Fig. 7 shows common mode voltages on the motor isolated neutral to ground on the output of a 4160 V drive system GTO inverter. The peak line to ground voltage, $V_{lk}$, is 4100 V and the waveform has a frequency of 60Hz. The peak neutral to ground voltage, $V_{ln}$, is 2500 V and has a frequency of 180 Hz. The operation of the output bridge creates a common mode voltage by exactly the same mechanism as the input bridge does, where the back emf of the motor is analogous to the line voltage. Thus, the worst
case condition for the common mode voltage is no-load full speed operation, as the phase back angle is 90 degrees for both the converters, and the motor voltage is essentially equal to the line voltage. The sum of both common mode voltages is approximately $V_m$ at six times the input frequency. Since the input and output frequencies are generally unequal, the machine experiences a waveform with beat frequencies of both input and output frequencies and there will be instances where twice the rated voltage is experienced. This is shown in Fig. 7.

An actual measurement of the common mode voltage on a 460 V ac, ASCI motor operating at rated speed and at no load showed peaks of 1000V phase-to-ground. This consisted of 375V peak, phase-to-neutral, 375V peak common mode plus 250V commutation spike. This is 2.66 times normal peak, phase-to-ground.

Ref. [16] investigates voltage to ground in LCI (Load Commutated Inverter) and CSI (Current Source Inverter) and concludes that a voltage of 2.4 per unit of the rated voltage can be achieved in most LCI circuit depending upon the bridge firing angles, line voltage, machine voltage and dc link reactors. Ref. [17] also discusses the problem of motor neutral to ground voltages for large medium voltage drives with special reference to retrofit of large constant speed line drive machines with variable speed drives.

**Effect of grounding**

The preferred method of system grounding to assure that the motor insulation system is not stressed beyond its design point is to provide an output isolation transformer and ground the secondary winding of the transformer, as shown in Fig. 8(a). The output isolation transformer primary winding insulation to ground can tolerate the neutral swings much better than the motor, particularly in retrofit applications.

Applying a transformer between drive and motor is, however, tricky due to low frequency requirements, residual dc offset in the drive and very high harmonics passing through the transformer. If the objective is only to support common mode voltages, then it is easier to put the drive isolation transformer (DIT) on the line side, as shown in Fig. 8(b). And secondary winding is left ungrounded.

![Diagram](image)

**Fig. 7.** GTO common mode voltage at the output with input neutral grounded

![Diagram](image)

**Fig. 8.** Alternate location of isolation transformers to withstand common mode voltages. In 8(a) and (b) the motor need not be designed for higher voltages.
The neutral of the filter capacitors on the output of inverter provide a convenient place to ground the load side of the inverter and a small resistor rated an ampere or so is sufficient to do this. The line to neutral voltages described above must then be taken into account for the transformer secondary insulation. In case of 12-pulse systems the line to ground voltages will appear between the wye and the delta secondary windings of the transformer and must be accounted for in the transformer insulation. The cables from the transformer secondary to rectifier must be rated for the higher voltages to ground. 5 kV grade cables will be adequate for 2.3 kV system. However, on 4.16 kV systems 5 kV grade cables with 173% insulation level will be required. Alternatively, 8 kV or 15 kV cables can be used.

A drive isolation transformer or an output isolation transformer increases the cost and reduces the efficiency of the drive, which is especially undesirable for high power drives. In a transformer less induction motor GTO drive system a line reactor may be used on the ac input side, Fig. 8(c). In this configuration the motor insulation must withstand twice the normal voltage stress to ground.

*Elimination of common mode voltage in the drive system*

Fig. 9 shows a 2300 V medium voltage drive system, where each motor phase is driven by three PWM cells. Each group of power cells are wye connected with a floating neutral, and it is powered by an isolated secondary winding of the drive isolation transformer. A greatly improved voltage waveform is obtained due to phase displacements in the transformer secondary windings and the harmonic distortion meets the limits set in [18] without filters. The common mode voltages are eliminated.

VI. HIGH IMPEDANCE FAULT DETECTION

In Fig. 9 the power cells common neutral point could be high resistance grounded. Alternatively a sensitive high impedance fault detection system can be included in the drive system electronics itself.

Fig. 10 shows the equivalent circuit for the ground fault detection in the drive system of Fig. 9. The values of the resistors $R_a$ and $R_b$ shown in the output attenuator module are applicable to a 4160 V drive. The capacitances of the transformer, motor and the drive system are ignored and a balanced three phase operation is assumed. Under no fault conditions and for equal values of $R_e$'s, the motor winding neutral is held at ground potential.

In Fig. 10, phase C is faulted to ground and $R_a$ is the fault resistance. With a series of circuit transformations, it can be shown that the sensing voltage $V_e$ developed across resistor $R_e$ in Fig. 10 under a single-line-to ground fault is given by the following expression:

$$V_e = (1.5)V_e R_e/(0.333R_e + R_a + R_b)$$

(7)

Where $V_e$ is the line-to-ground voltage output of the drive system.

Equation (7) shows that the voltage on the sense resistor is proportional to the output voltage. $V_e$ in the drive system can be set at 1 volt peak or a variable threshold of 0 to 5 volts can be programmed. Assuming a sensing voltage setting of 1 volt, and rated output voltage from the drive system, a high impedance fault of approximately 10 MΩ can be detected. The sensitivity will fall as the voltage from the drive system reduces.

In a practical installation the effect of capacitances and the ripple voltages generated in the drive system cannot be ignored. These impact the ground fault detection sensitivity. The frequency of output ripple voltage is a function of the phase multiplicity. Each power cell in Fig. 9 generates a ripple frequency of 600 Hz. A 4160 V drive system has five cells in series and the output ripple frequency is 3kHz. This PWM ripple will have arbitrary phase relationship with respect to fundamental.

![Fig. 9. An ac drive system with secondary phase multiplication, lower distortion and no common mode voltage generation.](image-url)
frequency. Thus, the capacitance effect predominates at the ripple frequency and referring to Fig. 11, the ripple voltage across motor terminal to ground is given by:

$$V_m = V_m \cdot \frac{C_i}{C_m} \quad (8)$$

Where $V_m$ is the ripple voltage to ground at the motor terminals and $V_m$ is the ripple voltage generated by the drive system. Considering 4160 V drive system, the ripple voltage is constant, 200V at 3 kHz. A ratio of $C_m/C_i$ of 20 gives a ripple voltage of 10 V at the motor terminals.

Thevenin equivalent circuit of Fig. 11 can be drawn as a balanced bridge circuit as shown in Fig. 12. This suggests that under no fault conditions, neither fundamental nor ripple frequency voltages appear across sense resistor $R_o$. Thus, nuisance trips should not occur. This assumes balanced capacitances in each phase.

Under a single-line-to-ground fault condition, both fundamental frequency as well as ripple frequency voltages will appear on sense resistor $R_o$. From Fig. 11, it can be shown that this voltage is given by the following expression:

$$V_s = \frac{R_o(V_c + 2V_r)}{(R_o + 0.333R_m)(3j\omega C_m R_s + 1) + R_s} \quad (9)$$

Fig. 11 shows an equivalent circuit diagram considering ripple voltages and capacitances. The ripple voltages are shown in series with the fundamental frequency voltages. $C_i$ is the capacitance of the DIT and the drive system, which is much smaller than the capacitance of the feeder cables to the motor and the capacitance of the motor windings itself, shown as $C_m$ in Fig. 11. Consider a 500-hp, 1800 rpm motor. The calculated capacitance of the motor and cables is 50nF. This gives a capacitive reactance of approximately 1kΩ at the ripple frequency.
Where all the symbols are as defined before.

From (9) and for a 4160V drive system with the values of attenuator resistances shown in Fig. 10 and a $V_L$ of 1 volt peak, the maximum motor neutral to ground voltage which will not cause a trip on bolted fault ($R_f = 0$) is 303 V crest or approximately 214 V rms. These voltages are small and don’t raise the insulation level of the windings of a 4160 V rated motor. The presence of a ripple voltage according to (9) on the sense resistor will further improve the sensitivity of the ground fault detection, though this ripple voltage may be filtered. Even at zero fundamental, there is a ripple voltage which appears across sense resistor $R_o$ under ground fault conditions.

VII. APPLICATIONS TO OTHER DRIVE TOPOLOGIES

The ground fault detection scheme described in the paper is generally applicable to other drive system topologies, but qualifications apply. All solid-state ac drives generate a fundamental output whose amplitude is approximately proportional to frequency. In addition there is superimposed high frequency voltage ripple created by the modulation process. The ac motors used with these drive systems have significant distributed capacitances to ground, compared to the transformer or the drive system itself. Thus any ac drive system, where the input source is isolated from the ground, through a drive isolation transformer as shown in Fig. 8(a), can be reduced to an equivalent circuit in Fig. 11. This assumes that capacitance of the transformer and drive system is small compared to motor and cables. If this condition is met, then regardless of the type of switching device, (GTO, transistor or IGBT), the described ground fault detection system can be applied. The resistor attenuators should be carefully selected, so that relation of (8) holds, i.e. distributed capacitances are sufficiently balanced and present much higher impedance than the resistor attenuator.

Thyristor dc drives generate a dc output voltage with a 360 Hz ripple voltage. The armature circuit of a dc motor has substantial capacitance to ground. Therefore, a thyristor dc drive with an input transformer could also utilize the ground fault detection circuit described in the paper. Fig. 13(a) shows the ripple voltage developed across the sensing resistor under no fault condition is only 20 mV peak and fig. 13(b) shows the voltage across the sensing resistor for a fault resistance of 150 kΩ. The ripple voltage, superimposed on the fundamental is hardly noticeable in Fig. 13(b).

The above calculations ignore: (1) effect capacitance of long drive motor cables, (2) the swings in the neutral above ground potential, as shown in Fig. 7. (3) asymmetry in the distribution system. Depending upon the drive system configuration, these can give rise to higher ripple currents returning to the sensing resistor. Their effect must be considered in selecting the settings of the ground fault protection. An ac source may serve a number of drives in a transformer-less system configuration as shown in Fig. 8(c) and result in nuisance operation of the ground fault detection system. Ref. [19] recommends the use of a high-pass filter in such cases, which will provide a low impedance path to the high frequency currents and, therefore, improve the sensitivity of the ground fault detection system.

Fig. 13(a): Ripple voltage developed across the sensing resistor in Fig. 11 under no fault conditions.

Fig. 13(b): Voltage across the sensing resistor for a 125 kΩ fault.

VIII. CONCLUSIONS

A properly implemented high resistance grounding system will meet the requirements of continuity of operations
on a single-line-to-ground fault and can be safely implemented for most of the drive systems. Other methods of system grounding can be applied, depending upon the considerations discussed in the paper. The guide lines presented in the paper are of a general nature, and the requirements of grounding of large medium voltage drive systems may be specific to the drive. The application of a high impedance fault detection system and the sensitivity calculations for a medium voltage drive system are demonstrated. As the sensitivity of the ground fault detection schemes improves, the future trends point towards high impedance grounded systems.

IX. REFERENCES

[14] NEMA MG1-1993(R1), Part 30, Application Considerations for Constant speed Motors used on a Sinusoidal Bus with Harmonic Content and general Purpose Motors used with Variable-Voltage or Variable-frequency Controls or Both.